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Study of shape of the yrast line and deformation changes in gadolinium isotopes

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Abstract : The Gamma ray studies of ^{147}Gd nucleus had been performed previously on the basis of gamma-gamma coincidence, angular distribution and excitation function measurements. In this nucleus (N = 83), two values for the effective moment of inertia are suggested which reproduce the energies of the non-yrast states, that are populated in the decay of the isomer. A comparison of the energy level patterns for the even gadolinium isotopes have been done by studying the changes in deformation through the so-called Gauge plots.

Keywords : Nuclear structure, yrast line, deformation, gauge space.

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Transitional nuclei with proton numbers Z = 64–68 and neutron numbers N = 82–86 have recently attracted considerable attention. In a pioneering study, Del Zoppo *et al* [1] demonstrated the existence of high spin isomers that decay by γ-cascades of high multiplicity in several of these nuclei. The transitional N = 88 isotopes are found to be characterized by a small prolate deformation at low spin, but a switch to oblate aligned particle non-collective yrast states occurs around $I = 30\hbar$, which is followed by return to moderate collectivity at yet higher spins ($I > 40\hbar$).

The studied nucleus ^{147}Gd with one valence neutron outside the N = 82 shell is essentially spherical in its ground state and its low spin structure is understood on the basis of the spherical shell model [2]. The nucleus was studied through measurement of the gamma radiation from the ^{122}Sn (^{30}Si, xn) reaction at E_{lab} = 160 MeV [3–5] by the Heidelberg double anti-compton spectrometer.

Shape of the yrast line :

The experimental yrast level energies *versus* $I(I + 1)$ for ^{147}Gd are given in Table 1 [and plotted in Figure 1]. The excitation energies are reproduced on an average by straight line which start at I = 0 with an excitation energy E_0 until $I = 41/2\,\hbar$. The fluctuations indicate that the yrast angular momentum does not originate from collective rotation where one would expect a smooth behavior of the yrast line. The I (I + 1) dependence is characteristic for the rotation of a rigid body or the average yrast line of the Fermi gas [6]. The good agreement for high spin values may be taken as evidence of the fact that Fermi gas model is a good approach for the few particle excitations in this nucleus.

In Figure 1, the extracted value for the effective moment of inertia $\Im_{eff}$ is 88 MeV^{-1} for $17/2 \le I \le 41/2$ whereas for $I \ge 43/2$, the value is 136 MeV^{-1}. The clustering of high-j orbital around the Fermi levels tends to decrease, the slope of the yrast line for spins less than the maximum possible

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with valence nucleons. For larger spins on the other hand, the necessity of promoting particles across the $Z = 64$ or $N = 82$ gap will result in a steeper yrast line. An example of the latter effect may be seen in the sharp increase in the slope of the yrast line just beyond spin $43/2\,\hbar$ (Figure 1). This change in the slope of the yrast line at high spins can be interpreted as a shape transition from spherical to oblate.

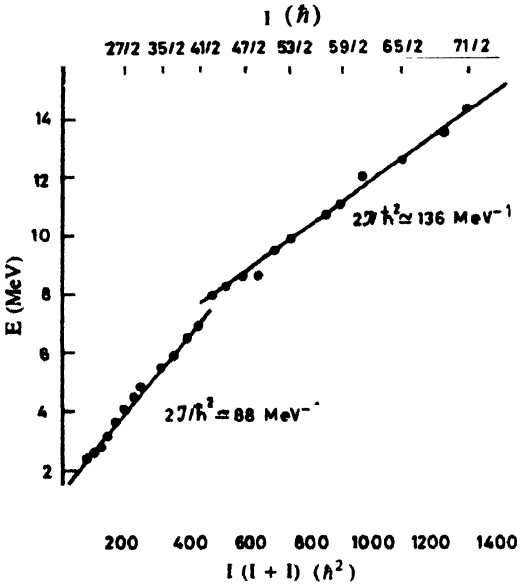

Figure 1. Excitation energies for yrast states in ^{147}Gd with the corresponding $I(I+1)$.

Table 1. Excitation energies for yrast states in ^{147}Gd [3–5] with the corresponding $I(I+1)$.

E(keV)	I	$I(I+1)$	E(keV)	I	$I(I+1)$
0.997	13/2	49	7.994	43/2	484
2.488	17/2	81	8.333	45/2	529
2.572	19/2	100	8.588	47/2	576
2.760	21/2	121	8.590	49/2	625
3.186	23/2	144	9.509	51/2	676
3.692	25/2	169	9.882	53/2	726
4.070	27/2	196	10.690	57/2	841
4.451	29/2	225	10.995	59/2	900
4.844	31/2	256	11.932	61/2	961
5.583	35/2	324	12.550	65/2	1089
5.923	37/2	361	13.448	69/2	1225
6.471	39/2	400	14.435	71/2	1296
6.906	41/2	441			

It seems that small oblate deformation ($\beta = -0.1$ to -0.2), shell effects and pairing correlations are responsible for the excess of the observed moments of inertia in ^{147}Gd over the rigid sphere values. $\Im_{\text{eff}}$ can be calculated from Mottelson and Valatin equation $2\Im/\hbar^2 = 36/A^{5/3}$ [7], assuming the fact that the pairing vanishes and the moment of inertia reaches the rigid sphere values ($\hbar^2/2\Im \approx 114$ MeV^{-1}) at a deformation appropriate to $\omega = 0$.

Gauge plots and deformation changes :

The changes in deformations can be explored through the so-called 'Gauge plots' [8] of neutron number (N) *versus* Fermi energy (λ), in analogy to the plots of I_x *versus* ω, which are frequently used for investigating rotational bands in ordinary space. In such a plot, one examines the difference in excitation energy E_x (I) for the ground-band members with spin (I) in pair of neighboring even-even nuclei. This energy difference, together with the two nucleons separation energy S_{2n}, specifies the Fermi energy (λ) as a function of spin. The Fermi energies are calculated from the relation

$$\lambda(N,I) = \frac{1}{2}\left[E_x(N+1,I) - E_x(N-1,I) - S_{2n}\right],$$

where N is the odd neutron number between the two even isotopes, which are compared. Figure 2 gives the results for the Gd nuclei calculated from the experimental energies [9–13] of the even isotopes with 82 to 90 neutrons [see also Table 2]. The separation energy (S_{2n}) for each neutron number is taken from Ref. [14]. In this figure, we see a

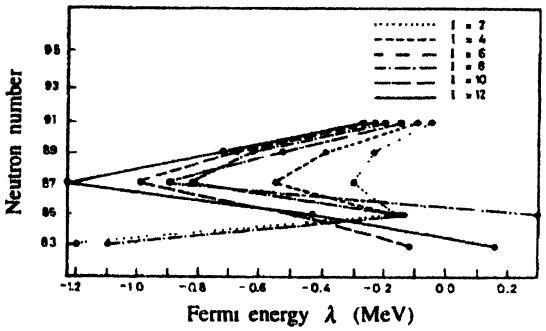

Figure 2. Back-bending plot showing the neutron number *vs* the Fermi energy for each spin in gauge space for the even Gd isotopes.

Table 2. Results of the Fermi energy (λ) for isotopes ^{147}Gd [9], ^{149}Gd [10], ^{151}Gd [11], ^{153}Gd [12] and ^{155}Gd [13].

	λ (MeV)				
	^{147}Gd	^{149}Gd	^{151}Gd	^{153}Gd	^{155}Gd
2	−1.1964	−0.1621	−0.3092	−0.2361	−0.0491
4		−0.1441	−0.5482	−0.3991	−0.0981
6		0.2889	−0.9042	−0.5241	−0.1490
8	−1.6944	−0.1551	−0.8222	−0.6171	−0.1961
10	−0.1144	−0.4870	−1.0030	−0.6771	−0.2380
12	−0.1616	−0.4321	1.2360	−0.7141	−0.2770

pronounced irregularity around neutron number 88, which reminds very much about the backbending or upbending (depending on I) behaviour.

The slope of the curves $N(\lambda)$ reflects the level density at the Fermi surface. An upbend (for example) in this curve (*i.e.* an increase of slope in a small energy region), indicates a sudden increase in level density. This tends to be

energetically unfavorable and must therefore be compensated, most likely by a change in deformation, typically an increase. Thus, in such a case, the upper branch in the $N(\lambda)$ curve is called the deformed branch (*e.g.* $N >$ 89 in Figure 2).

The calculation provides two values for the effective moment of inertia, which reproduces the energies of the non-yrast states that are populated in the decay of the isomer. In ^{147}Gd, a change in the slope of the yrast line at high spins was found and interpreted as a shape transition from spherical to oblate form. Information on the energy level patterns through the so-called Gauge plots for the Gd isotopes with neutron numbers 82–90 clearly shows the backbend between the spherical and the deformed nuclei.

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